NASA TT F-9435

NASA TT F-9435

AMPLIFICATION OF THE INFLUENCE OF EXTERNAL EFFECTS BY A p-n JUNCTION

Yu.F.Sokolov

N65-27690
(ACCESSION NUMBER)
(THRU) 1
8
(PAGES)
(CODE)
(NASA CR OR TMX OR AD NUMBER)
26
(CATEGORY)
FACILITY FORM 602

GPO PRICE $
OTS PRICE(S) $
Hard copy (HC) 1.00
Microfiche (MF) .50

Translation of "Ob usilenii effektov vneshnikh vozdeystviy p-n-perekhodom".
Radiotekhnika i Elektronika, Vol.10, pp.195-198, Jan.1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON JUNE 1965

NASA TT F-9435

AMPLIFICATION OF THE INFLUENCE OF EXTERNAL EFFECTS BY A p-n JUNCTION **/195

Yu.F.Sokolov

27690

Discussion of some results obtained by Stafeev which show that, if the current-carrier mobility in a semiconductor is changed by an external effect, the relative change in the current ($\Delta j/j$) flowing through a p-n junction with a thick base and the relative change in semiconductor conductivity ($\Delta\sigma/\sigma$) are related by the expression $\Delta j/j = K(\Delta\sigma/\sigma)$ where the amplification factor K is larger than unity. A formula for the maximum value of K is derived.

Author

It is generally known (Bibl.1) that, if any external effect changes the current-carrier mobility in a semiconductor, the relative change in the current $\Delta f/f$ flowing through a p-n junction with a thick base $(d/L \gg 1)$* built of this semiconductor and operating at a high level of injection will be connected with the relative change in the conductivity $\Delta\sigma/\sigma$ of the semiconductor by the relation

$$\Delta j / j = K(\Delta\sigma / \sigma), \tag{1}$$

where $K > 1$. The latter fact $(K > 1)$ makes it possible to state that the p-n junction intensifies the effect of the external influence on the semiconductor, and to designate K as the amplification factor.

In another paper (Bibl.2) K was calculated for the case where the external

* Notations as in an earlier report (Bibl.3). The calculations are performed in dimensional quantities.

** Numbers in the margin indicate pagination in the original foreign text.

factor is a magnetic field. Under the assumptions that: 1) a magnetic field does not change the mobility ratio b; 2) that cosh $(d/L) \gg b$; 3) $N = 0$; 4) that $\alpha(q/kT)v \gg 2b(d/L)e^{-dL}$ we obtained the expression /196

$$\cdot\frac{J}{p}a\frac{J4}{b}D\frac{z}{1}\approx y \tag{2}$$

In itself, eq.(2), although valid within the framework of the assumptions used in deriving it, is insufficient for calculating K under actual conditions, in view of the fact that the values of d/L and αv, as we will demonstrate, cannot be arbitrary.

First, d/L is bounded on top and, second, for any given d/L, also αv has an upper bound while $(\alpha v)_{max}$ depends on d/L. Thus, Karakushan (Bibl.2) solved only part of the problem of calculating K.

In this paper, we are making an attempt to calculate K in its final form. As had been done in the above paper (Bibl.2), we will assume that the external effect does not influence the value of b. It can be demonstrated that allowance for such an effect has only a slight influence on the final result. This is qualitatively clear from the fact that f depends bi-exponentially on d/L but less than exponentially on b [cf. eqs.(36) - (39), (Bibl.3)].

If the conductivity varies only on account of the variation in the mobility of the current carriers μ, then

$$\Delta\sigma/\sigma = \Delta\mu/\mu. \tag{3}$$

The relative variation in the current through a p-n junction is connected with the relative variation of the diffusion length by the relation

$$\frac{\Delta J}{J} = f\left(v, \frac{d}{L}\right)\frac{\Delta L}{L}, \tag{4}$$

where

$$f\left(v, \frac{d}{L}\right) = \left[\alpha\frac{q}{kT}(v-\varphi_0) - \frac{b\ln\frac{1+\cosh(d/L)}{2}}{b+\cosh(d/L)} - \frac{\cosh(d/L)}{1+\cosh(d/L)}\right]\frac{\sinh(d/L)}{b+\cosh(d/L)}\frac{d}{L}; \tag{5}$$

$$\varphi_0 = \frac{kT}{q}\ln\left[\left(1+\frac{b}{b+1}\frac{N}{P_n}\right)(1+\gamma_d)\right]. \tag{6}$$

Equations (4) - (6) were obtained on the basis of eqs.(36) - (39) of another paper (Bibl.3). The relation between f_{s0} and L was not taken into account. It follows from the well-known relation $L = \sqrt{(kT/q)\mu\tau}$ at τ = const that

$$\frac{\Delta L}{L} = \frac{1}{2}\frac{\Delta\mu}{\mu} + \frac{1}{2}\frac{\Delta T}{T}. \tag{7}$$

When the external effect is a magnetic field, we have $\Delta T = 0$ and from eqs.(3), (4), and (7) we obtain:

$$\frac{\Delta I}{I} = \frac{1}{2} f\left(v, \frac{d}{L}\right)\frac{\Delta\sigma}{\sigma}. \tag{8}$$

It is easy to see that f/2 coincides with eq.(2) if the adopted assumptions (Bibl.2) are satisfied.

If the external action heats the gas of the current carriers [for example (Bibl.4)], then

$$\frac{\Delta\mu}{\mu} = \lambda\frac{\Delta T_e}{T_e}, \tag{9}$$

where λ is the exponent in the relation connecting μ and T_e (T_e is the temperature of the current-carrier gas): $\mu \sim T_e^{\lambda}$. The value and sign of λ depend on the type of scattering. In lattice scattering, we have $\lambda = -1/2$, while in scattering on ionizing impurities, $\lambda = 3/2$ (Bibl.5). Others adopt the semiempirical value $\lambda \simeq 1$ (Bibl.4). Making use of eqs.(3), (4), (7), and (9), we get:

$$\frac{\Delta I}{I} = \frac{1}{2}\cdot\frac{\lambda+1}{\lambda} f\left(v, \frac{d}{L}\right)\frac{\Delta\sigma}{\sigma}. \tag{8a}$$

Comparison of eqs.(1), (8), and (8a) yields the conclusion that, in the general case,

$$K = \theta f(v, d/L), \tag{10}$$

where $\theta \sim 1$ and f is determined in eq.(5).

Let us consider the limits within which αv, d/L and thus also K may vary. /197

The equation for the volt-ampere characteristic of the form (Bibl.3)

$$I = I_0(d/L)e^{\alpha(q/kT)v} \tag{11}$$

and eq.(5) for f, obtained from eq.(11), are valid if (Bibl.3):

$$\gamma_0 \gg (1+\gamma_d)\frac{1+\cosh(d/L)}{2}, \tag{12}$$

where

$$\gamma_0 = \frac{(b+1)p_p e^{(q/kT)v_p}}{bN+(b+1)p_p}. \tag{13}$$

Since v_p cannot exceed the contact potential difference φ, the value of γ_0 has an upper bound. If we set the maximum value of v_p at which eqs.(11) and (5) are still valid at

$$v_{p\,max} = \varphi - \Delta, \tag{14}$$

where $\Delta \sim (2 - 3)(kT/q)$ (Bibl.6) then we find from eqs.(12) - (14) and eq.(6) that d/L has an upper bound: $d/L \leq (d/L)_{max}$. The value of $(d/L)_{max}$ is determined from the relation*:

$$\ln\frac{1+\cosh(d/L)_{max}}{2} = \frac{q}{kT}(\varphi - \varphi_0 - 2\Delta). \tag{15}$$

The meaning of condition (15) is that a substantial modulation of the conductivity of the entire quasineutral region [in the sense of the criterion (12)] can be realized only at $d/L \leq (d/L)_{max}$.

We pass next to an evaluation of the region of possible values of αv. From eqs.(12) - (14) it follows that**

$$\frac{q}{kT}(\varphi-\Delta) \geqslant \frac{q}{kT}v_p > \frac{q}{kT}\varphi_0 + \ln\frac{1+\cosh(d/L)}{2}. \tag{16}$$

---

* We replace the condition $\gg$ by the sign of equality, multiplying the right-hand side of eq.(12) by $e^{(q/kT)\Delta}$.

** In eq.(16) it was taken into consideration that, after taking the logarithms, the inequality $\gg$ could be replaced by the less strict inequality >.

According to eqs.(35) and (37) in an earlier report (Bibl.3), we have

$$\frac{q}{kT} v_m = \frac{q}{kT}\alpha(v-\varphi_0) + \frac{q}{kT}\varphi_0 + \frac{\cosh(d/L)}{b+\cosh(d/L)} \ln\frac{1+\cosh(d/L)}{2}. \tag{17}$$

Substituting eq.(17) into eq.(16), after a number of transformations and taking eq.(15) into account, we obtain

$$\frac{q}{kT}\Delta + \ln\frac{1+\cosh(d/L)_{max}}{2} - \frac{\cosh(d/L)}{b+\cosh(d/L)}\ln\frac{1+\cosh(d/L)}{2} \geqslant \frac{q}{kT}\alpha(v-\varphi_0) > $$
$$> \frac{b}{b+\cosh(d/L)}\ln\frac{1+\cosh(d/L)}{2}. \tag{18}$$

Obviously, other conditions being equal, K will be greater the greater $(q/kT)\alpha \cdot (v - \varphi)$, so that K_{max}, the maximum value of K for a given d/L, will be reached at

$$\left[\frac{q}{kT}\alpha(v-\varphi_0)\right]_{max} = \ln\frac{1+\cosh(d/L)_{max}}{2} - \frac{\cosh(d/L)}{b+\cosh(d/L)}\ln\frac{1+\cosh(d/L)}{2} + \frac{q}{kT}\Delta. \tag{19}$$

Substituting eq.(19) into eq.(5), we get

$$K_{max} = \theta\left[\ln\frac{1+\cosh(d/L)_{max}}{1+\cosh(d/L)} - \frac{\cosh(d/L)}{1+\cosh(d/L)} + \frac{q}{kT}\Delta\right]\frac{\sinh(d/L)}{b+\cosh(d/L)}\,\frac{d}{L}. \tag{20}$$

As already noted, the case $\cosh(d/L) \sim 1$ is not of interest here, and it is /198
therefore natural to consider $\cosh(d/L) \gg 1$. As a result, it follows from eq.(20) that

$$K_{max} \simeq \theta\left[\left(\frac{d}{L}\right)_{max} - \frac{d}{L} + \frac{q}{kT}\Delta - 1\right]\frac{e^{d/L}}{2b+e^{d/L}}\,\frac{d}{L}. \tag{20a}$$

It is obvious that the right-hand side of eq.(20a) has a maximum at some optimum value of $d/L = (d/L)_{opt}$, and that $(d/L)_{opt} < (d/L)_{max}$. Calculation of $(d/L)_{opt}$ and $K_{max\ max} = K_{max}[(d/L)_{opt}]$ for the case $e^{(d/L)_{opt}} \gg b$ leads to the expressions

$$\left(\frac{d}{L}\right)_{opt} = \frac{1}{2}\left[\left(\frac{d}{L}\right)_{max} + \frac{q}{kT}\Delta - 1\right], \tag{21}$$

$$K_{max\ max} = \theta(d/L)^2_{opt} \tag{22}$$

When the inequality $e^{(d/L)_{opt}} \gg 2b$ is not satisfied (this case is possible in p-n junctions of InSb, at $b \gg 1$), the value of $(d/L)_{opt}$ is shifted toward greater d/L.

It is clear from eqs.(21) and (22) that $(d/L)_{opt}$ and $K_{max\ max}$ depend only on the ratio $(d/L)_{max}$, i.e., in the final analysis, on the degree of alloying of the p- and n-regions of the p-n junction. In fact, from eq.(15) at $(d/L)_{max} \gg 1$ it follows that

$$\left(\frac{d}{L}\right)_{max} \simeq \frac{q}{kT}(\varphi - \varphi_0) - 2\frac{q}{kT}\Delta + \ln 4. \qquad (23)$$

Noting that $\varphi = (kT/q)\ \ln(P/p_n)$ (P being the concentration of acceptors in the p-region) and bearing eq.(6) in mind, we obtain

$$\left(\frac{d}{L}\right)_{max} \simeq \ln\frac{(b+1)P}{bN+(b+1)p_n} - 2\frac{q}{kT}\Delta - \ln\frac{1+\gamma_d}{4}, \qquad (23a)$$

$$\left(\frac{d}{L}\right)_{opt} \simeq \frac{1}{2}\left[\ln\frac{(b+1)P}{bN+(b+1)p_n} - \frac{q}{kT}\Delta - \ln\frac{1+\gamma_d}{4} - 1\right]. \qquad (21a)$$

Assume that $\Delta \sim 3(kT/q)$ and $\gamma_d \sim 1$*. In this case,

$$\left(\frac{d}{L}\right)_{opt} \simeq \frac{1}{2}\left[\ln\frac{(b+1)P}{bN+(b+1)p_n} - 3\right]. \qquad (21b)$$

Obviously, the closer the conductivity of the n-region is to the intrinsic conductivity and the greater P**, the greater will be $(d/L)_{opt}$. Let us estimate $(d/L)_{opt}$ and $K_{max\ max}$ for actual cases.

The value of $[bN + (b + 1)p_n]$ in intrinsic germanium at room temperature is $\sim 10^{13}$ cm^{-3}. At lower temperatures (but higher than those corresponding to the freeze-out of the current carriers), this value is about 10^{12} cm^{-3}. At present, it is possible in InSb to reach a concentration of about 10^{13} cm^{-3},

---

* The value of γ_d in the case $d/L \gg 1$ is unknown. It may well be, however, that γ_d is less for $d/L \gg 1$ than for $d/L \ll 1$. In the latter case, for N = 0, we would have $\gamma_d \sim 10$ (Bibl.7).

** P should not exceed the concentration corresponding to degeneration into p-regions.

which will remain constant down to helium temperatures. As for P in the cases of both Ge and InSb, we may assume $P \sim 10^{18}$ cm^{-3}. Thus we may consider, in our estimate, that $(b + 1)P/[bN + (b + 1)p_n] \sim 10^5$. Hence, $(d/L)_{opt} \sim 4$ and $K_{max\ max} \sim 16\ \theta$.

BIBLIOGRAPHY

1. Stafeyev, V.I.: Fiz. tverd. tela, Vol.1, No.6, p.841, 1959.
2. Karakushan, E.I. and Stafeyev, V.I.: Fiz. tverd. tela, Vol.3, No.3, p.677, 1961.
3. Sokolov, Yu.F.: Radiotekhn. i Elektronika, Vol.8, No.3, p.471, 1963.
4. Lifshits, T.M., Kogan, Sh.M., Vystavkin, A.N., and Mel'nik, P.G.: Zhurn. Eksp. Teor. Fiz., Vol.42, No.4, p.959, 1962.
5. Smit, R.: Semiconductors (Poluprovodniki). IL (State Publishing House for International Literature), 1962.
6. Adirovich, E.I. and Kuznetsova, Ye.M.: Radiotekhn. i Elektronika, Vol.4, No.10, p.1708, 1959.
7. Sokolov, Yu.F.: Radiotekhn. i Elektronika, Vol.9, No.4, p.660, 1964.

Institute of Radio Engineering and Electronics, USSR Academy of Sciences

Received Jan.29, 1964